Coexistence of a weakly-deformed band in a strongly-deformed nucleus

W. D. Kulp[1], J. L. Wood[1], K. S. Krane[2], J. Loats[2], P. Schmelzenbach[2], C. J. Stapels[2], R.-M. Larimer[3], E. B. Norman[3]

[1] *School of Physics, Georgia Institute of Technology, Atlanta, GA 30332-0430*

[2] *Department of Physics, Oregon State University, Corvallis, OR 97331-6507*

[3] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*

(October 27, 2002)

A weakly-deformed band J^{π} (E_x keV) 0^+ (1182), 2^+ (1418), 4^+ (1701) is identified in the strongly-deformed nucleus, ^{154}Gd. Detailed γ-ray spectroscopy following the beta decays of ^{154}Eu ($J = 3$), ^{154g,m_1,m_2}Tb ($J = 0, 3, 7$) are used to establish this structure. The structure is explained in terms of a pairing isomer which results from the $\nu[505] \uparrow$ Nilsson intruder orbital.

21.10Re, 23.20.Lv, 27.70.+q

Shape coexistence in nuclei, i.e., the existence of deformed excited states in spherical nuclei [1,2] and superdeformed excited states in nuclei with weak to moderate deformation [3] is a widespread and well-established phenomenon. However, the converse possibility, the widespread occurrence of weakly-deformed excited states in strongly-deformed nuclei, has never been addressed. The probable reason for this is that this second possibility for shape coexistence is much harder to realize experimentally. Weakly-deformed states lack the easily identified collective characteristics of strongly-deformed states (closely-spaced bands of rotational states with strongly-enhanced intraband $E2$ transitions).

Historically, the low-lying excited states of ^{154}Gd have been classified [4] into rotational bands characteristic of a strongly-deformed symmetric top (axially symmetric rotor). This classification strongly supports a picture of a variety of intrinsic excitations with essentially uniform rotational energy constants, and, thus, essentially uniform deformations. In contrast, Shahabuddin *et al.* [5] argue that strong (t,p) population of a 0^+ level at 1182.1 keV and a 2^+ level at 1418.1 keV indicates that these are associated "spherical "states in a "deformed "nucleus. However, this argument is based on the nonobservation of a 0^+ level at 1295.5 keV (previously associated with the 1418.1 keV level as members of the 2β band [6]) and lacks spectroscopic evidence which directly links the level at 1182.1 keV (unobserved in β decay studies) to the 1418.1 kev level.

As a result of a γ-ray spectroscopy program that we have initiated to make a systematic study of the collective excitations in the $N = 90$ nuclei, we have not only observed population of the 0^+ 1182.1 keV state through β decay, but also we have identified a weakly-deformed band (cf. Figure 1) built upon that state. We present details which identify this band, not only to establish a new type of collective structure in nuclei, but also to illustrate the detailed spectroscopy that is necessary to identify weakly-deformed states in a strongly-deformed nucleus.

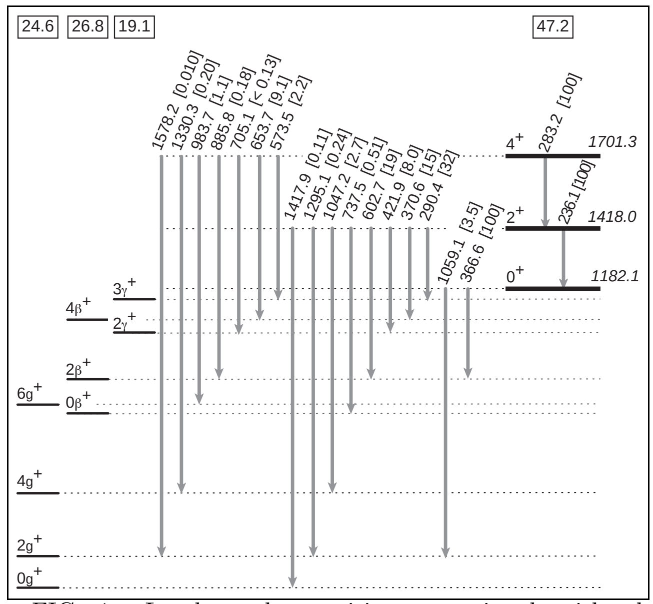

FIG. 1. Levels and transitions associated with the weakly-deformed intruder structure in ^{154}Gd. The rotational parameters (in keV), above each rotational band show that the band built on the 0^+ (1182) level has a weaker deformation than the lower-lying bands. This smaller deformation is also indicated by the wider separation between levels in this band compared with the spacing in lower-lying bands. Relative $B(E2)$ values (in brackets) show that the strongest collective transitions are the in-band 236 and 283 keV γ rays.

Excited states in the nucleus ^{154}Gd are accessible through the β decay of four long-lived isotopes: ^{154}Eu (8.6 yr, $J^{\pi} = 3^-$), ^{154}Tb (21.5 h, $J = 0$), ^{154}Tb (9.4 h, $J^{\pi} = 3^-$), and ^{154}Tb (22.7 h, $J^{\pi} = 7^-$). These decays provide the means to study low-spin states below 2 MeV in ^{154}Gd in great detail ($Q_{\beta^-}(^{154}\text{Eu}) = 1968.5 \pm 1.1$ keV, $Q_{\text{EC}}(^{154}\text{Tb}) = 3560 \pm 50$keV [7]). For our studies, the Tb sources were produced by the ^{153}Eu(^{4}He$, 3n$) and ^{154}Gd(p,n) reactions using 38 MeV ^{4}He and 9.75 MeV p beams from the LBNL 88" cyclotron; the Eu sources used were both commercially obtained and produced by the ^{153}Eu(n,γ) reaction in the Oregon State University reactor. Coincidence measurements were carried out using the "8π spectrometer", an array of 20 Compton-suppressed Ge detectors which provided good long term stability (system energy resolution ~2.5 keV at E_γ = 1 MeV for periods of ~1 week), excellent peak:total ratio (~0.5 at 660 keV), and low incidence of summing (source-to-detector distance 22 cm). Source strengths were typically ~10 μCi.

Three levels are associated with the new band presented in Figure 1: the 0^+ 1182.1, 2^+ 1418.0, and 4^+ 1701.3 keV levels. Of these, only the 2^+ 1418 level is already well established through β decay. The 0^+ 1182 level, although previously reported in transfer reaction [5] and (n,γ) studies [8] is observed through the β decays of ^{154}Eu and ^{154g,m_1}Tb for the first time. In contrast with the accepted level scheme [4] for ^{154}Gd, our coincidence data from the decay of ^{154m_1}Tb indicate that only one state, the 4^+ level at 1701.3 keV, exists in the energy range 1698-1704 keV with $J^\pi = 2-4$. Transitions from the previously reported levels at 1698.5 keV and 1702.0 keV are inconsistent with the γ-ray energies and intensities found in coincidence, cf. Figure 2, with a new 484.6 keV γ ray depopulating the known [4] 4^- level at 2185.6 keV. While the γ-ray coincidence data strongly support this band structure, evaluated data [4] associate the 0^+ 1182 with a 2^+ level reported at 1294.2 keV and the 2^+ 1418 with a 0^+ level at 1295.5 keV, which suggests a very different picture of the low-lying structure of ^{154}Gd.

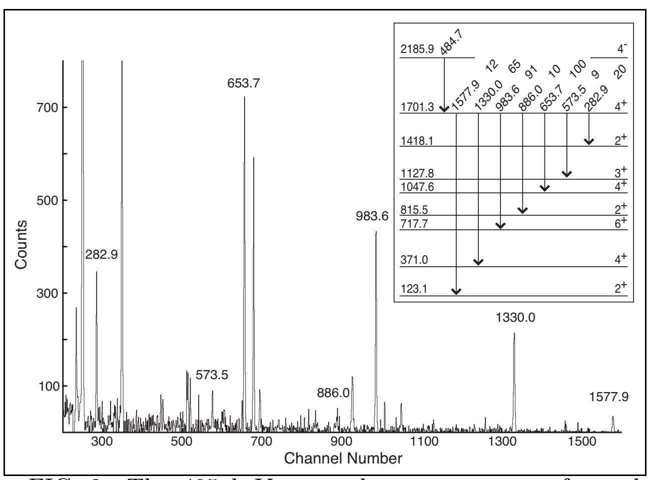

FIG. 2. The 485 keV γ-gated γ-ray spectrum from the ^{154}Tb decay study showing transitions from the 4^+ level at 1701.3 keV identified in Figure 1. The 485 keV γ ray has an intensity of 0.5% in the ^{154}Tb ($J = 3$) decay relative to the 123 keV γ ray.

The band formed by the 0^+ 1182, 2^+ 1418, 4^+ 1701 states has the characteristics of a structure which is considerably less deformed (much larger energy spacings) than the lower-lying states in ^{154}Gd. Moreover, the nearby higher-lying states in ^{154}Gd are consistent with band structures which have deformation similar to the ground state, indicating that the wide spacing in the new band is not due to mixing distortions. This immediately raises the question of whether or not the present studies have failed to populate any low-spin (positive-parity) states in ^{154}Gd below ~1500 keV. To address this question, we have adopted two strategies. The first has been to look in our data for the various reported gamma rays which have led, in other studies, to proposing the 1294.2 and 1295.5 keV levels. The second has been to assess the "completeness"of the ^{154}Gd level scheme deduced in the present work.

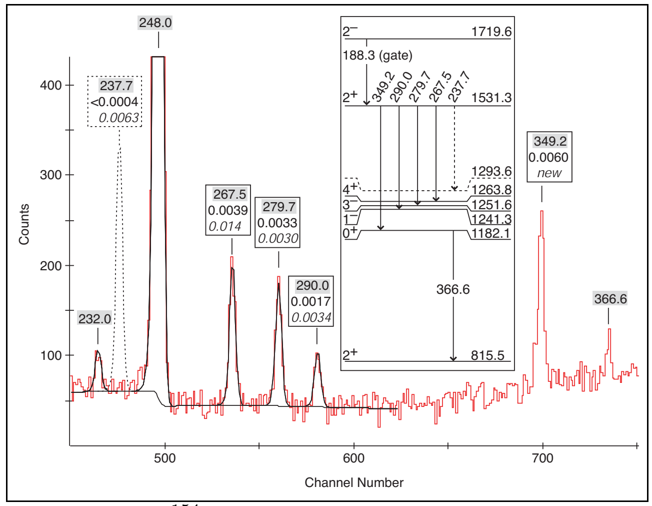

FIG. 3. The ^{154}Eu decay 188 keV γ-gated γ-ray spectrum. Boxes indicate the energy and measured I_γ (per 100 β decays) for transitions out of the level at 1531.3 keV which is fed directly by the 188 keV γ ray (cf. reported [4] intensity in italics). The 238 keV transition feeding the reported $(2)^+$ level at 1293.6 keV is missing (dotted lineshape indicates the expected intensity). Doublets at 267.7 (1264 $\to$ 996, I_γ = 0.012) and 290.0 keV (1418 $\to$ 1128, I_γ = 0.0016) were previously unresolved. A new transition observed at 349 keV feeds the 0^+ level at 1182.0 keV.

Studies which have reported gamma rays to and from the 1294.2 and 1295.5 keV levels have been limited to ^{154}Eu$(\beta^-)^{154}$Gd [6], ^{154g,m_1,m_2}Tb$(\beta^+/\mathrm{EC})^{154}$Gd [9,10], and ^{153}Gd$(n,\gamma)^{154}$Gd [8]. There are serious inconsistencies [4] between these studies. A striking image of these inconsistencies is presented in Figure 3, where we show a portion of the spectrum of γ rays de-exciting the 1531.3 keV 2^+ state, populated in the decay of ^{154}Eu. The 349 keV γ-ray is a new transition which feeds the 1182 keV 0^+ state. The 267 keV γ-ray is part of a previously unresolved doublet, one part of which feeds the 1264 keV 4^+ state. The location for ~237 keV γ-rays, which would feed levels at 1294-1295 keV, is marked. We set an upper limit for a 237.0 keV γ-ray of 0.0003, cf. 0.017 [4], $(I_\gamma(1274.4) \equiv 100)$. A similar method may be used to set upper limits for all γ rays which have been associated with the 1294.2 and 1295.5 keV levels (cf. Table I). The reported 615.1 keV E0 transition which Sousa *et al.* [9] assign as 1295.8 $\to$ 680.7 keV cannot be directly

TABLE I. Total transition intensity out of excited states in ^{154}Gd populated through the β decay of ^{154}Eu per 100 β decays. Data from the adopted [4] ^{154}Eu decay scheme and from reported neutron capture studies of Spits, *et al.* [8] are included for reference. The notation "1°"and "2°"indicates observed primary and secondary γ-ray intensities following neutron capture (per 1000 neutrons captured).

J^{π}	E_x	/100 β D_{Eu}†	/100 β D_{Eu} [4]	/1000 n (n,γ)2° [8]	/1000 n (n,γ)1° [8]
2^+	123.1	89.5	89.1	59.7	0.08
4^+	371.0	7.98	7.68	14.1	-
0^+	680.7	0.277	0.271	3.41	0.7
2^+	815.5	2.98	2.98	9.26	2.33
2^+	996.3	23.1	23.1	8.14	0.08
4^+	1047.6	0.280	0.264	2.04	-
$1,2^+$	1136.0	< 0.004	0.010	-	-
0^+	1182.1	0.016	-	1.45	2.4
	1233.1	< 0.002	0.003	-	-
4^+	1263.8	0.797	0.768	1.40	-
	1277.0	< 0.004	0.014	0.16	-
$(2)^+$	1293.6	< 0.002	0.006	-	-
$(2)^+$	1294.2	< 0.004	0.016	0.49	-
0^+	1295.5	< 0.004	-	0.23	-
2^+	1418.1	0.134	0.114	2.53	0.08
$(1,2^+)$	1510.1	< 0.001	0.024	-	-
2^+	1531.3	0.63	0.56	1.95	0.75
4^+	1645.8	0.17	0.16	0.56	-

†This work (decay of ^{154}Eu).

addressed by this study; however, Spits and Van Assche [8] refute this.

Assessing completeness in a decay scheme study is extremely difficult. One may use rotational band patterns and population systematics and argue that, if higher-lying levels with the same spin-parity as the levels in question are populated then the levels in question should be seen. To quantify this, we have used the method described by Currie [11] to set upper limits on the intensity of γ-ray transitions unobserved in this study which are associated with previously reported levels.

In Table I we present the population intensities of all reported excited states in ^{154}Gd up to $\sim$1.5 MeV, which (may) have $J^{\pi} = 0^+, 2^+, 4^+$, as seen in previous γ-ray spectroscopic studies and compare the reported intensities with that determined in the present work. We limit population intensities from our studies to the decay of ^{154}Eu due to the difficulties in separating the decays of ^{154g,m_1,m_2}Tb and the resulting ambiguity in setting reasonable upper limits on the population intensity. For comparison, we include two investigations [6,12] and an evaluation [12] of ^{154}Eu(β^-)^{154}Gd which report the intensities of very weak γ-ray lines and an investigation [8] of ^{153}Gd(n,γ)^{154}Gd. These results suggest that any 2^+ state below 1418 keV would be observable in the present work. While it could be argued that the lower Q value of the ^{154}Eu decay precludes population of a 0^+ level at 1295.5, the next reported [4] excited 0^+ state above the 1295.5 keV state is at 1574.0 keV. We observe population of this state in the decay of ^{154g}Tb with an intensity of 1.6% which can be compared with our observed population of the 1182.1 keV 0^+ state of 3.9%. If a 0^+ state exists in ^{154}Gd at 1295.5 keV, we deduce that it is populated a factor $\sim$30 lower than the systematic trend observed in this study.

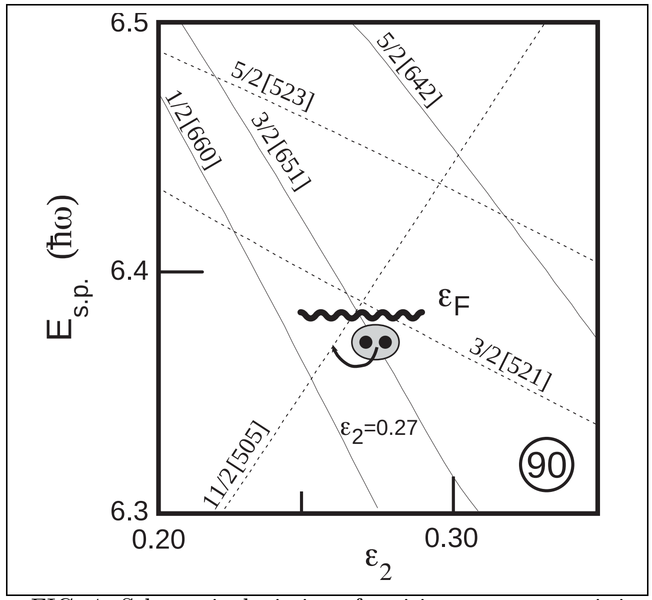

FIG. 4. Schematic depiction of exciting a neutron pair into the steeply "upsloping" $\frac{11}{2}^-$ [505] Nilsson configuration. This produces a pairing isomer (a state with a different pairing gap than the ground state) which has a less prolate shape than the neighboring "downsloping"Nilsson configurations. The Fermi energy for $N = 90$ is shown for $\varepsilon_2 = 0.27$ which corresponds to a deformation appropriate for ^{154}Gd. (The Nilsson diagram is adapted from the *Table of the Isotopes* [13]).

The low-energy band structure of ^{154}Gd has been addressed theoretically using the dynamic deformation model [14,15], the interacting boson model[15-18], and the "projection model " [19]. All of these investigations discuss ground, "beta", and "gamma"bands, but only Kumar *et al.* [15] discuss higher-lying ($\beta\beta$, $\beta - \gamma$, ...) bands. In particular, a $\beta\beta$ two-phonon vibrational band structure is predicted which has a larger energy spacing than the lower-lying bands. However, the bandhead of this $\beta\beta$ band is predicted to be 700 keV higher than the 1182 keV level found experimentally and the predicted intensities of transitions out of this band are not in agreement with the experimental data. Indeed, some of the $B(E2)$ ratios predicted by Kumar are significantly greater than the experimental ratios, cf. Table II.

A simple interpretation of the present structure can be achieved using a Nilsson diagram and pairing, and is depicted in Figure 4. The steeply upsloping $\frac{11}{2}^-$ [505] Nilsson configuration, if occupied by a neutron pair, will favor a smaller deformation than the neighboring (downslop-

TABLE II. Comparison of theoretical and experimental values of $B(E2)$ ratios from transitions out of the band built on the 0_3^+ state in ^{154}Gd. Theoretical values are predicted by the dynamic pairing plus quadrupole model (DPPQ) [15] for the "$\beta\beta$"band, 0^+ (1842), 2^+ (2156), 4^+ (2490). Experimental ratios from the decays of ^{154}Eu and ^{154}Tb are results of this work for the band presented in Figure 1, 0^+ (1182), 2^+ (1418), 4^+ (1701).

Initial Level I_i	Transition ratio I_f/I'_f	$B(E2)$ ratio DPPQ	$B(E2)$ ratio Exp.
$2_{\beta\beta}$	$0_g/2_g$	29.5	0.46
	$4_g/2_g$	54	11.3
	$0_\beta/2_\beta$	0.01	0.027
	$4_\beta/2_\beta$	2.7	0.79
	$0_\beta/0_g$	0.6	4.6
	$2_\beta/2_g$	2210	79.2
	$2_\beta/2_\gamma$	4.4	2.4
	$2_\gamma/2_g$	505	33.3
	$4_\beta/4_g$	110	5.6
$4_{\beta\beta}$	$4_\beta/4_g$	1.3×10^5	45.5

ing) Nilsson configurations. The $\frac{11}{2}^-$ [505] configuration has been pointed out by Peterson and Garrett [20] as having the potential for giving rise to "pairing isomers" [21]. The present work confirms this prediction. Further, the implied isolation [20] of the $\frac{11}{2}^-$ [505] configuration would explain the observation [5] of strong population of the 1182 and 1418 keV states in the $^{152}\mathrm{Gd}(t,p)^{154}\mathrm{Gd}$ reaction.

The present result is also a realization of predictions by Chu *et al.* [22] and suggests that the interpretation given here could be readily tested using in-beam γ-ray spectroscopy following heavy-ion induced neutron-pair transfer on ^{152}Gd. The combination of Coulomb excitation and nucleon-pair transfer in heavy ion reactions offers a potential experimental means for observing collective bands built on pairing isomers. These structures will not be near the yrast line in deformed nuclei and so the selectivity provided by the identification of the outgoing ion, in conjunction with γ-ray spectroscopy of the residual nucleus (or the reverse in inverse kinematics) offers a unique spectroscopic probe for such structures.

In summary, we have measured γ-ray transitions from excited states in ^{154}Gd populated in the β decay of the long-lived isotopes ^{154}Eu and ^{154g,m_1,m_2}Tb. A weakly-deformed band structure in the strongly-deformed nucleus ^{154}Gd has been identified using γ-ray coincidence spectroscopy. This unprecedented structure is interpreted as a "pairing isomer"based upon the steeply upsloping $\frac{11}{2}^-$ [505] Nilsson configuration.

We wish to thank colleagues at the 88" cyclotron for assistance in the experiments, and Dennis Burke and Paul Garrett for valuable disscusions. This work was supported in part by DOE grants/contracts DE-FG02-96ER40958 (Ga Tech); (OSU); DE-AC03-76SF00098 (LBNL).

[1] K. Heyde *et al.*, Phys. Repts. **102**, 291 (1983).
[2] J. L. Wood *et al.*, Phys. Repts. **215**, 101 (1992).
[3] B. P. Singh, R. B. Firestone, and S. Y. Chu, Nucl. Data Sheets **78**, 1 (1996).
[4] C. W. Reich and R. G. Helmer, Nucl. Data Sheets **85**, 171 (1998).
[5] M. A. M. Shahabuddin, D. G. Burke, I. Nowikow, and J. C. Waddington, Nucl. Phys. **A 340**, 109 (1980).
[6] R. A. Meyer, Phys. Rev. **170**, 1089 (1968).
[7] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[8] A. Spits and P. Van Assche, Technical Report No. BLG 703, SCK/CEN (unpublished).
[9] D. C. Sousa, L. L. Riedinger, E. G. Funk, and J. W. Mihelich, Nucl. Phys. **A 238**, 365 (1975).
[10] H. Yamada, H. Kawakami, M. Koike, and K. Komura, J. Phys. Soc. Jpn. **42**, 1448 (1977).
[11] L. A. Currie, Anal. Chem. **40**, 586 (1968).
[12] M. A. Hammed, I. M. Lowles, and T. D. Mac Mahon, Nucl. Instr. Methods **A 312**, 308 (1992).
[13] R. B. Firestone, *Table of the Isotopes: 1998 Update*, 8th ed. (John Wiley & Sons, Inc., New York, 1998).
[14] H. Tagziria, W. D. Hamilton, and K. Kumar, J. Phys. G. **16**, 1837 (1990).
[15] K. Kumar, J. B. Gupta, and J. H. Hamilton, Aust. J. Phys. **32**, 307 (1979).
[16] C. S. Han, D. S. Chuu, and S. T. Hsieh, Phys. Rev. C **42**, 280 (1990).
[17] P. O. Lipas, P. Toivonen, and D. D. Warner, Phys. Lett. B **155**, 295 (1985).
[18] P. Van Isacker, K. Heyde, M. Waroquier, and G. Wenes, Nucl. Phys. **A 380**, 383 (1982).
[19] P. O. Lipas *et al.*, Phys. Scr. **27**, 8 (1983).
[20] R. J. Peterson and J. D. Garrett, Nucl. Phys. **A414**, 59 (1984).
[21] I. Ragnarsson and R. A. Broglia, Nucl. Phys. **A 263**, 315 (1976).
[22] S. Y. Chu *et al.*, Phys. Rev. C **52**, 1407 (1995).